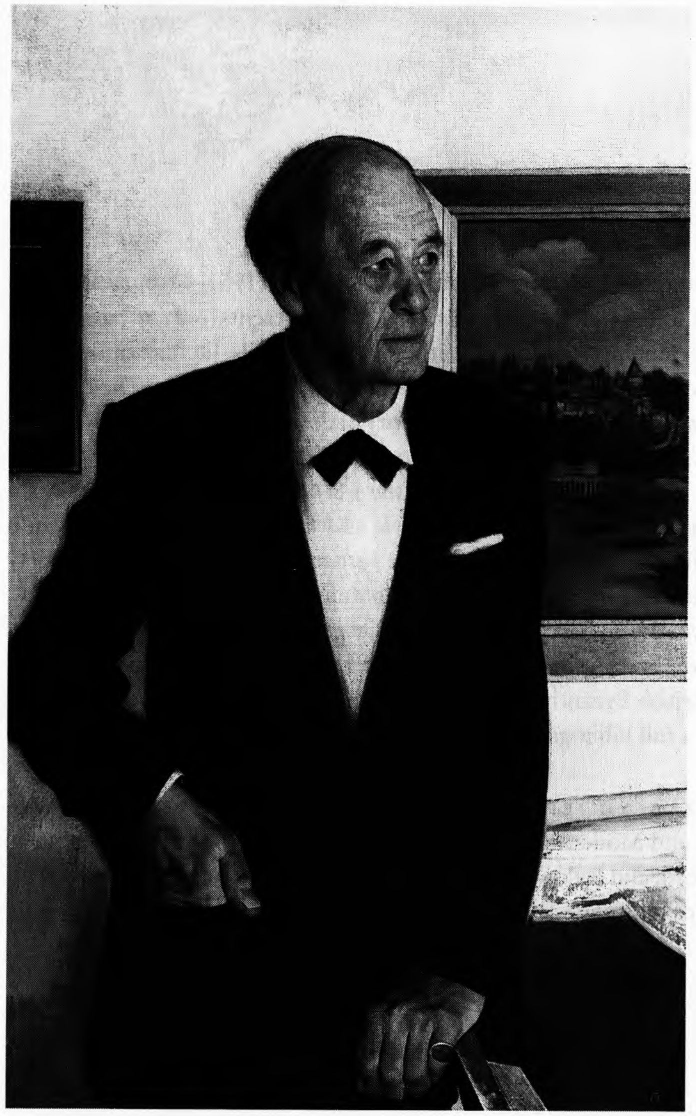

Byzantine Style, Religion and Civilization

In Honour of Sir Steven Runciman

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15 | 'Greek fire' revisited: recent and current research

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Sir Steven Runciman's now classic study, *The Emperor Romanus Lecapenus and his Reign*, published in 1929, presents still one of the most insightful and scholarly accounts of the Byzantine empire in the first half of the tenth century. Yet in his discussion of the defeat of the Russian attack on Constantinople in 941, while noting the role played by 'Greek fire' in a victory in which fifteen warships are supposed to have defeated a vastly superior force of enemy vessels, he says little more than that it was 'the awe-inspiring novelty' of the attack using this weapon to which the imperial ships owed their rout of the raiders.[1] But what lay behind this awe-inspiring novelty? 'Liquid fire' (ὑγρὸν πῦρ), the 'secret weapon' of Byzantium, has remained a fascination for many students of the medieval eastern Roman empire, and its exact workings are still the subject of heated debate. Historically, it seems to me doubtful that it radically affected the general evolution of the Byzantine state and its neighbours, although the point can be argued; and the very fact of its mystery amply demonstrates the fact that it seems to have conferred few, if any, long-term technological benefits on those who employed it. Nevertheless, because the 'secret' was lost, it retains a certain fascination.

Some twenty-six years ago I wrote, with my colleague Maurice Byrne, a short article for *Byzantinische Zeitschrift*, in which we set out the basic evidence from the Byzantine and other western sources for what the Byzantines or east Romans called 'liquid fire' or 'sea fire' (θαλάσσιον πῦρ).[2] As we pointed out then, this incendiary weapon is generally known today as 'Greek fire', although this is a term employed almost entirely by western commentators, and one which is used in a way which frequently fails to distinguish between the Byzantine weapon, which was quite clearly from the sources a type of flame-thrower, and the regular and long-established use of incendiary missiles hurled by hand or by catapult or other mechanical means.[3] Although Liutprand of Cremona uses the term *ignis graecus* of the Byzantine weapon in the Rus attack on Constantinople in 941, as does the Norman chronicler Geoffrey Malaterra for the year 1081, it is generally used indiscriminately by western writers of both types of weapon, and more often than not of projectiles filled with, or carrying, combustibles such as pitch or oil.[4] While the lack of technical detail makes it difficult to be sure,

it seems likely that the Arabs possessed such a weapon by the 830s; and they may in turn have been responsible for its transmission to China thereafter.[5] It first appears clearly attested in Byzantine sources in accounts of the naval battles associated with the Arab blockades of Constantinople in the years 674–8; it last appears explicitly in the 1180s, and while it may still have been employed in the 1190s, by 1204 it appears no longer to have been available to imperial warships.[6]

Since the original article appeared, several scholarly contributions to the debate have been published, and we would like here briefly to review the conclusions they reach in the light of a series of experiments carried out in 2002 in the process of making a television documentary about 'liquid fire'. One of the significant absences in most discussions to date has been the practical experiment, since it is apparent from many contributions that the evidence is interpreted entirely in theoretical terms. We tried in the 1970s to conduct a small-scale experiment, and did achieve some useful results; but we have now been able, through the additional funding available through the production company, to construct a full-scale working version of a device that would project effectively liquid fire at a target, and destroy it. In what follows we will review, first, the sources and the arguments that have been advanced to interpret them and, secondly, describe the experiment conducted and its outcome.

The debate

The first point to make is that it seems now widely agreed that liquid fire was, in fact, a petroleum-based weapon,[7] and had no connection whatsoever with explosive materials or mixtures, whether sulphur-, quicklime- or saltpetre/gunpowder-based (as proposed, for example, by Berthelot in the late nineteenth century and by Zenghelis in the early 1930s, and followed by a number of more recent commentators, including Stratos).[8] The last attempt to suggest that it was an explosive was by Pászthory in 1968, but his argument ignores some of the most important evidence, in particular the petroleum component, which was clearly crucial for the Byzantines. And there is not a shred of evidence to suggest that any form of gunpowder-based or explosive-based weapon was known or available to the western world before the arrival of gunpowder proper in the fourteenth century.[9] The tenth-century *De administrando imperio* gives a list of major sources of supply of crude oil in the northern Pontic and Caucasus regions, for example.[10] Most recently, the debate has been renewed with the appearance

of a useful discussion by Th. Korres, entitled simply 'Liquid fire',[11] which sets out to show that the real nature of 'Greek fire' was in fact a catapult-thrown projectile filled with combustible material, although he agrees that petroleum was the main ingredient.[12] Before we look at this theory, therefore, let us briefly review the testimony of the sources.

The evidence

The discussion is well-enough known for it to be unnecessary to repeat and to explain every scrap of evidence here. We will, therefore, describe briefly the chief characteristics of the Byzantine device, and set out in each case the source of the description or evidence from which these characteristics may be derived. To some extent we will repeat here what was said in the article of 1977.

That petroleum was the chief substance projected is quite clear from the reference in the *De administrando imperio*. The text reads:

Ἰστέον, ὅτι ἔξω τοῦ κάστρου Ταμάταρχα πολλαὶ πηγαὶ ὑπάρχουσιν ἄφθαν ἀναδιδοῦσαι.

Ἰστέον, ὅτι ἐν Ζιχίᾳ πρὸς τὸν τόπον τῆς Πάγης, τῆς οὔσης εἰς τὸ μέρος τῆς Παπαγίας, ἐν ᾧ κατοικοῦσι Ζιχοί, ἐννέα πηγαὶ εἰσὶν ἄφθαν ἀναδιδοῦσαι, πλὴν οὐχ ὁμοχροοῦσιν τῶν ἐννέα πηγῶν τὰ ἔλαια, ἀλλὰ τὰ μὲν ἐξ αὐτῶν εἰσιν ἐρυθρά, τὰ δὲ ξανθά, τὰ δὲ μελανώτερα.

Ἰστέον, ὅτι ἐν Ζιχίᾳ ἐν τῷ τόπῳ τῷ καλουμένῳ Πάπαγι, ἐν ᾧ καὶ πλησίον ἔστι χωρίον ἐπονομαζόμενον Σαπαξί, ὃ ἑρμηνεύεται 'κονιορτός', ἔστιν ἐκεῖσε βρύσις ἄφθαν ἀναδιδοῦσα.

Ἰστέον, ὅτι καὶ ἑτέρα βρύσις ἔστιν ἐκεῖσε ἄφθαν ἀναδιδοῦσα ἐν τῷ χωρίῳ τῷ καλουμένῳ Χαμούχ. . . . Ἀπέχουσι δέ οἱ τοιοῦτοι τόποι ἀπὸ τῆς θαλάσσης ὁδὸν ἰδιοκαβάλλου ἡμέρας μιᾶς.

Ἰστέον, ὅτι ἐν τῷ θέματι Δερζηνῆς πλησίον τοῦ χωρίου τοῦ Σαπικίου καὶ τοῦ χωρίου τοῦ ὀνομαζομένου Ἐπισκοπείου, ἔστιν πηγὴ ἄφθαν ἀναδιδοῦσα.

Ἰστέον, ὅτι ἐν τῷ θέματι τοῦ Τζιλιάπερτ ὑπὸ τὸ χωρίον τὸ Σρεχιαβαρὰξ ἔστιν ἐκεῖσε πηγὴ ἄφθαν ἀναδιδοῦσα.

Outside the city of Tamatarcha[13] are many wells yielding naphtha.

In Zichia,[14] near the place called Pagi,[15] which is in the region of Papagia and is inhabited by Zichians, are nine wells yielding naphtha, but the oils of the nine wells are not of the same colour, some of them being red, some yellow, some blackish.

In Zichia, in the place called Papagi, near which is a village called Sapaxi, which means 'dust', there is a spring yielding naphtha.

There is yet another spring yielding naphtha, in the village called Chamouch. . . . These places are distant from the sea a journey of one day without changing horses.

In the province of Derzene,[16] near the village of Sapikion and the village called Episkopion, is a well yielding naphtha.

In the province of Tziliapert,[17] below the village of Srechiabarax, there is a well yielding naphtha.

The various sources complement one another in telling us details of the weapon. The fire or flame itself is described as 'liquid' or 'sea' fire, as noted already, or as prepared (ἐσκευασμένον/σκευαστόν) or 'sticky' (κολλυτικόν) fire; in popular language it was referred to as λαμπρόν, or 'brilliant/radiant'. It is usually projected or thrown from 'siphons', mounted on warships, either in the bows alone, from a platform decked over and protected by planking, or in addition on either side amidships.[18] Its operation is accompanied by a loud roaring and thick smoke, and it is not easy to use in anything other than relatively calm conditions. It can be employed at close range.[19] The operator is referred to as a σιφωνάτωρ (*siphonator*) and, from the written sources at least, there appears to be only one for each device.[20]

From this evidence, several elements or processes necessary to the operation of the device can be distinguished: the *siphon*, or pump (although at Leo, *Tactica* XIX.6 the word *siphon* seems to refer to the whole device); a tube, clad in or made of bronze,[21] which could be directed left and right as well as up and down, so must have been mounted on some type of swivel arrangement (and is hence referred to also as a *strepton*);[22] and a hearth or brazier on which the oil was heated.[23] Other elements include tin (for soldering or brazing parts of the device?) and flax (for the hearth and/or for the ignition-torch at the nozzle?).[24]

The question of how the device actually worked is the real problem. The term *siphon* had a variety of applications: a hose or water-lead; a tube or siphon (used to draw wine from a cask); a small water reservoir; a small earthenware pot (the last two deriving from the second). It was certainly used of a pump, as an early ninth-century hagiographical text, the *Vita Stephani iunioris*, makes clear: τοὺς ἐν αὐτῷ τῷ τόπῳ ἱσταμένους ὑδροστάτας τῶν ἐμπρησμῶν, οὕσπερ σίφωνας καλοῦσιν ('the water-engines for fires in that place, which are called *siphons*').[25] It could also refer to a tube through which liquids could be projected under pressure, as a very clear description in the *Poliorketika* of Apollodorus (c. 130 AD) makes clear.[26] In the context of liquid fire, it appears to have the specific meaning of a hose or tube through which or from which the liquid fire was projected.[27] Sometimes the terms *strepton* and *siphon* are used of the whole apparatus, making it difficult to establish what each specific term actually meant. But so far these accounts suggest that oil was pumped from a reservoir, which was heated over a hearth or

grate, and projected under pressure through a swivel nozzle or tube. A ninth-century Latin account makes this process fairly clear:

Nam pergentibus Saracenis ad bellum navali certamine in prima fronte navis facta fornace illi insidunt vas eneum his plenum subposito igne, et unus eorum fistula facta aerea ad similitudinem quam rustici squitiatoriam vocant, qua ludunt pueri, in hostem spargunt.

For when the Saracens go to war in a naval battle, they [sc. the Byzantines] make a furnace in the bows of their ship, on which they rest a vessel of bronze filled with these oils, and place fire under it, and one of the crew, by means of a tube made of bronze such as that called by country folk a squirt, with which boys play, sprays at the enemy.[28]

In his book on the subject as well as in a recent summary article, Korres argues that the weapon consisted primarily not of a pump and tube-projector but of earthenware pots (*siphounia*) filled with inflammable material, launched by torsion-powered *ballistrai*, and by means of a bronze tube attached to the slider (the running block with channel for the bolt or arrow), also called a *siphon*. Thus he interprets the term *strepton* as a torsion-powered catapult.[29] He objects that a simple force-pump could not achieve sufficient velocity to project the liquid oil; that the system would be blocked by residues in the mixture; that it would not be possible to maintain pressure for long enough for the weapon to be effective against enemy vessels; and that a single operator (as suggested by some of the sources) would not be able to synchronize the components of the system in battle conditions.[30] He notes also that the tube (which is envisaged as a large *solenarion*, or arrow-guide, as used on smaller hand-held bows) was the innovative element in the whole apparatus.[31] Korres's arguments raise some important questions about the type of artillery available to the Byzantines in the period in question, as well as about the interpretation of the sources.

But on closer examination, we immediately come up against a number of difficulties. That *siphon* could also refer to a type of small pot is not in doubt; but it is worth noting – as has recently been demonstrated – that the word was employed to describe a particular type of pot, a clay vessel constructed with an integral tube used for drawing off liquids (usually wine) from a larger container or vat.[32] That it could mean 'tube' is also clear, as some of the texts already noted suggest – the fact that the oil or flame is projected from or out of a *siphon* is sufficient to suggest this – and this is confirmed by some Arabic texts.[33] But quite clearly it could also be used of a pump: the reference in the *Vita Stephani iunioris* refers explicitly to the large wooden bar (referred to as the 'loom') which was attached to the pump, clearly a reference to the cross-bar inserted through the central beam or stanchion to work the reciprocating cylinders of a force-pump, or to the bar affixed to the arm of a single-cylinder pump.[34]

It should further be noted that in a document of 949 each *dromon* is equipped with three *siphones*, while reference is also made to forty other warships – *ousiaka* (*chelandia*) – as being provided with two *siphones* each.[35] Liutprand of Cremona's account of the imperial warships in action against the Rus fleet in 941 repeats this – that the fifteen old *dromones* brought out to combat the attackers were each equipped with liquid fire projectors at bows, stern and sides. The Russian *Primary Chronicle* notes that the fire was projected or dropped on the Rus boats 'from pipes'.[36] Equipping warships with only two or three projectiles is obviously nonsensical; so that unless we are to assume that the catapults which are held to have projected the pots in question were also described as *siphones* (which seems highly unlikely), this interpretation becomes more than improbable. Furthermore, in the tenth-century treatises on naval warfare, garbled in places though they are, and dependent for much of their technical language on misunderstood terms from their Roman or Hellenistic sources, it is quite clearly stated that in the standard *dromon* the liquid fire *siphon* has built above it a gangway and false deck with a plank breastwork to protect the soldiers who are posted there to repel enemy boarders; which surely removes any possibility that we are dealing here with a catapult, and any doubt that *siphon* was the term by which the Byzantines themselves referred to the device as a whole.[37]

The interpretation of *siphon* as a pot hurled by catapult also ignores the pictorial evidence which, however stylized and unrealistic, nevertheless is based upon the notion that fire was projected from a tube, and not as a missile (Matritensis vitr. 26–2, f. 34v.b (11th century); and Vat. graec. 1605, f. 185, C1 (11th century)).[38] Now in this connection it is interesting that the emperor Leo VI refers to hand-held *siphones* as something 'recently devised', and it is notable that the tenth-century text entitled *Parangelmata poliorketika*, ascribed in the tradition to 'Hero of Byzantium' (from which the Vatican manuscript drawing comes), notes that if infantry soldiers armed with hand-held *strepta* shoot fire at the enemy from siege-ladders, they will drive their foe from their defensive positions (a description not dissimilar to the account of the use of these weapons in the contemporary or near-contemporary *Sylloge tacticorum*).[39] These two texts confirm, first, that *siphon* and *strepton* were used interchangeably in certain contexts (a hand-held torsion catapult would certainly have been a novelty!).

Secondly, since the illustration accompanying Heron's text in Vat. graec. 1605 depicts such a soldier holding a tube or *siphon* from which flames

are emitted, we can dismiss the notion that the *siphones* in this particular instance were pots or containers thrown at the enemy. It needs also to be emphasized that in most of the texts in which liquid fire is mentioned as an element in the armament of ships, the possibility of hurling pots or containers filled with inflammables, including 'liquid' or 'prepared' fire, by catapult is mentioned *in addition to* both the regular *siphones* mounted on the ships and the 'newly-invented' *cheirosiphones*. This was an entirely standard practice across the ancient and medieval worlds, and there is no reason to doubt that such containers could be hurled with reasonable accuracy by skilled artillerymen.[40]

Given the several possible meanings attributable to the word *siphon*, given the specification of one variety as a *cheirosiphon* (thus clearly differentiating it from the other type of *siphon*), and given the ambiguity of some of the references to this hand-held weapon, it is entirely possible that the term *cheirosiphon* or *cheirosiphounion* could refer both to hand-hurled pots or 'grenades', distinct from the fixed-position projectors mounted on the warships, and to small liquid fire projectors, although the evidence of the Vatican manuscript would suggest that the latter is to be preferred. We will return to the *cheirosiphon* below.

The word *strepton* – from στρέφω – means '(easily) twisted or turned'; 'bent'; 'curved' (LSJ). In Hero of Alexandria's account of a water pump fire-extinguisher, for example, the swivel nozzle which can be moved to direct the jet of water is referred to as an ἐπίστρεπτον στόμιον.[41] The tenth-century Suda lexicon gives several definitions for the word στρεπτός (only in the masculine, however, not neuter) including both a type of necklace and a type of loaf, but no mention of artillery or weaponry of any sort is made.[42] We are not persuaded that Korres is right to argue that it refers to the twisted skeins of rope which constituted the springs of torsion-powered *ballistae*, and hence to the machine as a whole. First, the standard word for such catapults – βάλιστρα – was still in regular use; second, the manuals on artillery offer a series of specific technical terms for the torsion springs themselves (such as τόνος) which would certainly have been employed had this been necessary. *Strepton* is never found with this meaning.[43] In addition, there is considerable doubt as to whether such torsion weapons were still employed in the Byzantine world after the fifth century (although this is debated).[44] Given the convergent use of *siphon* and *strepton* noted already, there can surely be little doubt that the latter term does indeed refer to the 'easily turned' swivel projection tube.

A final question arises over the descriptive terms used in some of the accounts. In his account of the Byzantine measures preceding the Arab attack on Constantinople in the years 674–8, Theophanes notes that the emperor

Constantine IV 'built large cauldron-fire-bearing biremes and *dromones* equipped with siphons'. For the siege of 717–18, he likewise notes that the emperor (Leo III) 'constructed fire-bearing siphons which he placed on *dromones* and biremes . . .'[45] In the first case, it is difficult to know whether there is an intended difference between the 'cauldron-fire-bearing' vessels and those 'equipped with siphons'. Is it possible that the 'cauldron-fire' is the oil in containers which provided supplies for the ships carrying the actual siphons? This seems inherently unlikely given the fleet's proximity to its base and the difficulties of transferring the oil from one vessel to another. Or are the different terms merely stylistic, describing biremes and *dromones* which actually carried the same equipment? In favour of this is the fact that the second account, for the siege of 717–18, refers simply to both *dromones* and biremes equipped with 'fire-bearing siphons'.

In contrast, the ninth-century Latin account (see above) seems to suggest a syringe dipped into a vat of hot oil and then squirted – a very simple device, which would perhaps be the precursor of the simple 'hand-siphon'. Yet it is highly likely that this is again a not entirely inaccurate, but nevertheless garbled and perhaps 'common-sense' account, since it is clear from the other sources that the liquid fire projector was somewhat more complex than this – it was a whole machine that could be referred to by a single term, either *siphon* or *strepton* or by a neutral term such as *skeue* (σκεύη), meaning simply device, apparatus or equipment.[46] This is not to suggest that such simple syringe-like projection tubes were not also employed throughout the medieval world for other purposes – there is a good deal of evidence from Islamic contexts to show that this was the case, for example.[47] Even Theophanes's term 'fire-bearing *siphon*' implies something more than an ordinary squirt, else why specify in this way rather than refer simply to fire shot through a squirt, particularly in view of the fact that *siphon* does bear a technical meaning, 'pump'? Since it is generally agreed that the sort of pump with which we are here concerned was well known to the Byzantines, there seems no reason to doubt that this was the basis for the liquid fire projector, although we may equally suspect that various improvements may have been added as experience accumulated over the years.

The experiment

Whereas our original suggestion was that the liquid fire was projected by pressure augmented by the pump, however it seems in fact more probable that it was chiefly by means of a force-pump that the desired effect was achieved. In September 2002, as part of the work for a television programme

on the subject,[48] we built and tested a small version of the pressure-container model, and although from the technological and metallurgical perspective there is no doubt that the Byzantines could have constructed a sealed container with appropriate entry- and exit-pipes opened and closed by simple valves, using traditionally available materials (bronze, iron, leather, etc), the major problem in heating the container (necessary to increase pressure) was the rapid development of porosity in the joints, causing the heated liquid to penetrate the metal at critical points, and thus proving to be inherently and unavoidably unstable.

The model designed for the pressure container experiment was constructed from two identical cast bronze vessels each in the shape of a large cylinder, closed at one end, with the dimensions: 320 mm internal height, 220 mm internal diameter, and a wall thickness of 10 mm. At the open end of each vessel a wide flange was made so that when the two vessels were joined together the flange would provide a large surface area for the seal. These vessels were made using a wooden pattern, which was moulded and cast with simple clay-bonded sand. The bronze used for the experiment is generally termed a leaded gunmetal consisting of 85 per cent copper, 5 per cent tin, 5 per cent lead and 5 per cent zinc. Many variations of this alloy have existed in the past since ancient times, often excluding the zinc; but for Byzantine metallurgy of the period zinc appears frequently to have been used and added to the melt in its mineral form of calamine. Sand casting was chosen as a method certainly available in the Byzantine period, although it is equally possible for any such vessels to have been cast using the lost-wax method (*cire perdue*), which had been employed throughout the region for casts and large-scale sculpture since antiquity.

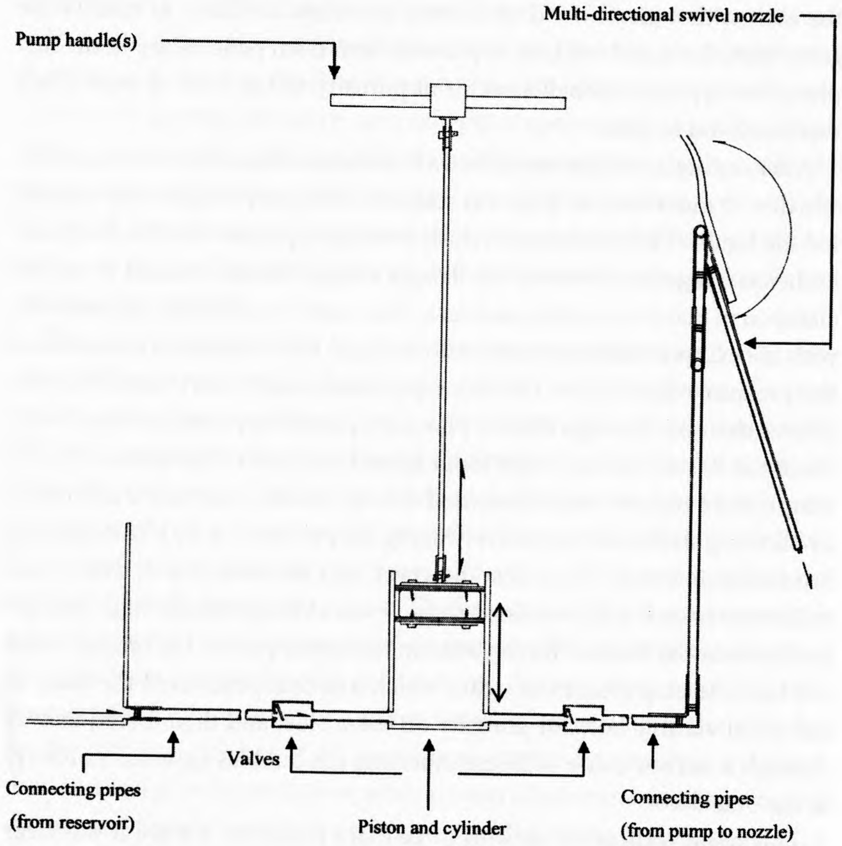
Sand casting typically produces a chilled cast (hot molten metal is poured into a cold mould), resulting in a tight and fine-grain structure in the alloy. But as is common with castings of this thickness, a considerable degree of porosity was found at the ingates (the pipes that allow the metal to flow into and out of the mould). Porosity is the bane of the founder or metallurgist, and is caused by the uptake of hydrogen when the bronze is in a molten state and in the melt. Porosity occurs when the cast cools and hydrogen is expelled as the metal crystals start to solidify, while simultaneously oxygen is taken up in the metal, forming cuprous oxide. These two gases are found in the atmosphere and in moisture present in the crucible, the furnace and the charge. This in turn causes the so-called 'steam reaction', whereby the two gases are reunited to form high-temperature steam. This outcome is difficult to avoid, and would have been dealt with by the founder, from ancient times just as today, by the addition of degassing fluxes, or stirring

the melt with a green wood stick. Both methods act either to remove the gases from the liquid melt, or to prevent them from penetrating in the first place. But typically a small amount of porosity would exist in most heavy casts, as it did in ours.

After casting one of the vessels had a hole cut into the centre of its base, into which a 30 mm diameter pipe was soldered, thus providing an exit channel for the liquid. The two bronze vessels were then placed with the flanges of each vessel together. Between the flanges a ring of leather soaked in oil was clamped in place to function as a seal. This vessel was then placed vertically with the exit pipe at the top, and with a simple turn valve at its end to act as the pressure release valve. For this experiment, water was poured into the bronze chamber through the exit pipe on top, and the pressure valve closed. Once the device was set, a gas torch heated the base of the bronze. As the temperature rose we were concerned that the leather seal would fail, either by allowing steam out and thus reducing the pressure, or by burning as the bronze became hot. It was clear, however, that the leather seal, simple and rudimentary as it was, remained sound even at temperatures high enough to discolour the bronze. But an area on the upper part of the bronze vessel did fail, releasing plumes of steam which had first penetrated the body of the metal via tiny holes of porosity on the inside, and then forced its way through a narrow route of interconnecting gas bubbles (gaseous porosity) to the outside.

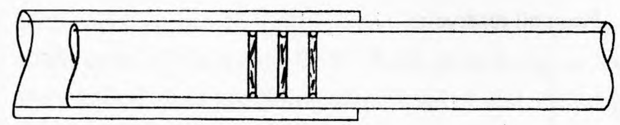
This result confronted us with three main problems. Firstly, it was clear that the pressure required to project a jet of oil a sufficient distance would not be provided through these means. Secondly, and more importantly for the crew of a warship, it appeared likely that any gases or vapour emitted from the bronze vessel might collect in the protected hull of the ship and catch fire. Thirdly, and most dangerous of all, if a high pressure were achieved there would be a high chance that the superheated oil might explode, thus turning the device into an impromptu bomb. We considered lining or coating the inside of the bronze with lead or tin in order to reduce the negative effect of the porosity, but in general our conclusion was that this type of device was too temperamental and dangerous to be used even in war, at least with the limited knowledge we have of the options available to the Byzantine engineers of the period.

We decided, in consequence, to abandon this approach, and constructed instead a full-scale working model of a projector consisting of three main elements: a two-man double-cylinder force-pump; a reservoir for the oil; and a swivel nozzle which could be operated by a single individual (Fig. 15.1). The pump was connected to the reservoir[49] by a pipe of bronze, closed by a



15.1 Schematic side elevation of the apparatus

simple screw-tap for safety reasons (but in the event found to be unnecessary in actual operating conditions); and the pump fed the oil it drew from the reservoir directly to the swivel nozzle, mounted on a simple metal stand. In order effectively to control the inward and outward flow of oil through the pump, simple one-way valves were built. The whole was constructed of traditional materials: the pump pistons were of wood coated in hemp and flax, for example; the cylinders themselves were of cast bronze; the piping of bronze/copper; and the valves of bronze/iron. Joints were sealed with hemp, pitch and soldered, where appropriate, with tin. The whole process imitated that described for the construction of a double-cylinder water pump in Hero of Alexandria's *Pneumatics* (I, 28).[50] It is important to bear in mind at this point that, sophisticated as the device may appear from this description of its several parts, each element can be shown to have had either its historical equivalent, or to be capable of being manufactured



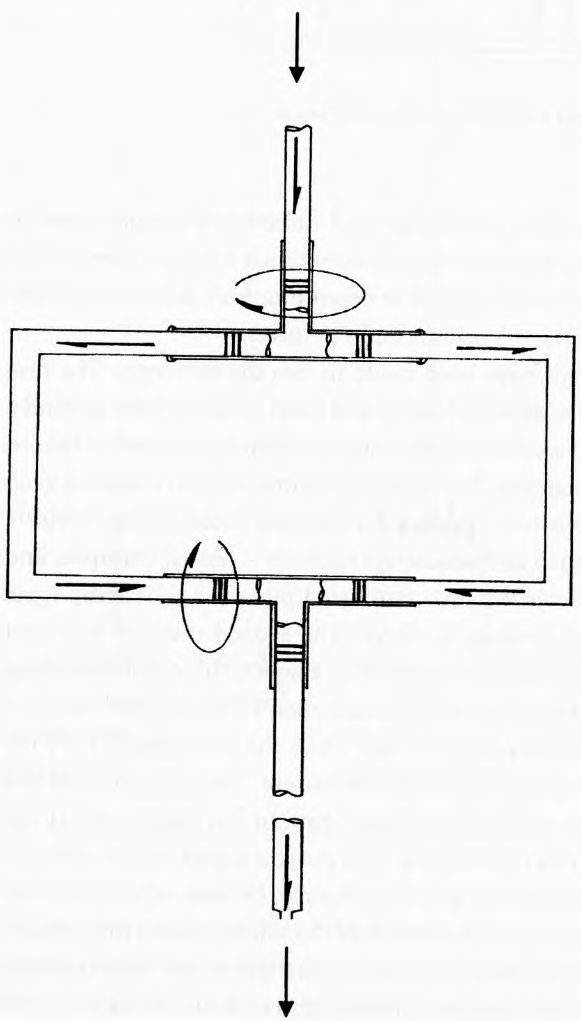
15.2 Method of sealing joints and joining sections of pipes

using appropriate Byzantine technology and exceedingly simple material solutions. In considering the issues in generating such a design, therefore, it was relatively straightforward to break it down into four key components: the pipes, the swivel joints, the pistons and the valves.

Pipes: historically pipes have been made in two distinct ways. The first method is to take thin flat sheets of metal and bend or wrap them around a wooden former to create a cylinder. The seam can then be soldered or brazed as appropriate for the material. It is relatively simple work to create an even shape with equal proportions, perfect for creating interlocking intricate composite structures, such as musical instruments – horns, trumpets and so forth. Structurally however, such fabricated pipes are inherently weak if subject to substantial pressure or force. The second method is to cast sections of pipe using the lost-wax method. In essence, this requires making a wax version of whatever is to be cast, and then to invest that wax in a heat-proof material such as plaster or clay. Once the investment is dry the wax is burnt out and replaced with molten bronze. The advantage of this method is that, once an appropriate master pattern has been made, it can readily and consistently be reproduced. This process is particularly efficient for mass-produced complex designs. Structurally, because of the necessity for castings to have a minimum 3–4 mm wall thickness to allow the metal to flow evenly throughout the shape/matrix, the strength of the form is greatly increased, and can therefore deal with mechanical movement, friction, and substantial temperatures.

Swivel joints: the main challenge in producing successful movable joints is to obviate the liquid seeping through when turning or applying pressure or force. In our experiment, this was overcome with surprising ease using entirely traditional techniques, by cutting grooves and roughening the outer surface of each interlocking section of pipe. After preparing the surface, hemp fibres were bound around these grooves and smeared with tallow (pig fat) to provide a seal, and then hammered into place (Fig. 15.2). In practice, all of these joints proved very effective, revealing no seepage. The measuring and fitting of each section could be done without the need for any precision, as each section of pipe could be filed individually and repeatedly offered

From oil reservoir



To nozzle

15.3 Multi-directional/universal swivel apparatus

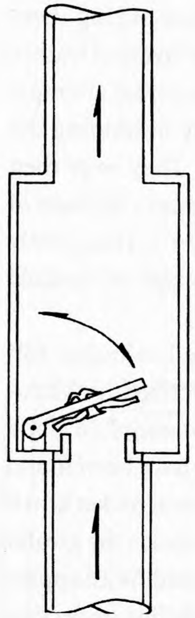
up to the other in order to make the necessary adjustments. The hemp completed the seal very effectively by taking up any residual gaps (Fig. 15.3).

Pistons: the cylinders consisted of two cast bronze casings, 320 mm high, 200 mm internal diameter with a wall thickness of 10 mm. The interior of each cylinder was turned on a lathe for ease, but could also have been finished using scrapers and files. The pistons were made from wooden rods

with metal connecting plates riveted to their upper ends and linking them to the arms of the rocker. To the head of each piston several layers of leather were nailed, thus providing some level of seal, although in initial attempts this was found by itself to leak very badly. The answer lay in binding the piston heads with hemp and copious amounts of tallow. They were then rammed back into the cylinders (compare Philo of Byzantium's account of Ctesibius's fitting of piston head to cylinder, *Belopoeica* 77 f.). This greatly improved the efficiency of the pump, with a low percentage of residual leakage.

The construction and orientation of piston, rocker and cylinders follow the design by Ctesibius (third century BC), and described by Vitruvius (*De architectura*, X.7) and Hero of Alexandria (*Pneumatica* I.28) for a water pump/fire-extinguisher, examples of most of which have been found archaeologically.[51] With the two vertical cylinders and a central rocker arm it was possible to apply substantial force on each downward stroke; the greater the length of the pivoting arm the greater the leverage achieved. With appropriate manpower, and a reducer nozzle at the end of the swivelling projection pipe (thus further increasing pressure at the point of emission), we were able to project a jet of liquid high enough and far enough to reach a target vessel without any danger of coming into direct contact. With hindsight the design would have been greatly improved by placing the whole pump mechanism inside the reservoir, thus losing no liquid from the system (see below) – Roman wooden water pumps were generally operated with the block submerged, for example. It was noted that, even with leaks from each piston, the working prototype could be made safe from any flames merely by covering the connecting pipes in sand.

Valves: the valves proved to be the most complicated components of the design to make. It was clear from the sources that both an inlet and an outlet valve were required in order to progress the flow of liquid from reservoir to jet. Again, antiquity offers two good solutions to this problem. The first is the disc valve, whereby a disc with a locating arm on its upper side is placed in a vertical pipe, rising up as pressure increases beneath it, and dropping under water pressure back down to a collar, to stem the reverse flow (cf. Hero's 'Valverde Huelva' pump). Our design, in contrast, and since it depended on a horizontal flow, employed the second type of simple flap valve, known as an *Assarium* valve after Hero's description (Fig. 15.4). These valves open in the direction of the flow and close on the pressure being reversed. Four such valves were constructed and fitted in cast sections or housings, as in the Valverde Huelva pump; the housings are slightly wider than the connecting pipe, 50 mm in internal diameter and 80 mm in length. These sections



15.4 Valves

were then fitted to the connecting pipes immediately before and after the cylinders. Inside each housing a small disc pivoted on a hinge, held in place with an iron pin. Although Hero describes the use of two flat plates that fell perfectly together in his design, the principle is the same. The face of each disc was covered with leather, which in turn, when in its sealed position, pressed against a thin raised ring of bronze to create a tight fit. When tested together with two modern equivalent valves on one side, and the two reconstructed medieval valves on the other, it was found that the reconstructions in fact allowed greater volumes of liquid through, and under higher pressure.

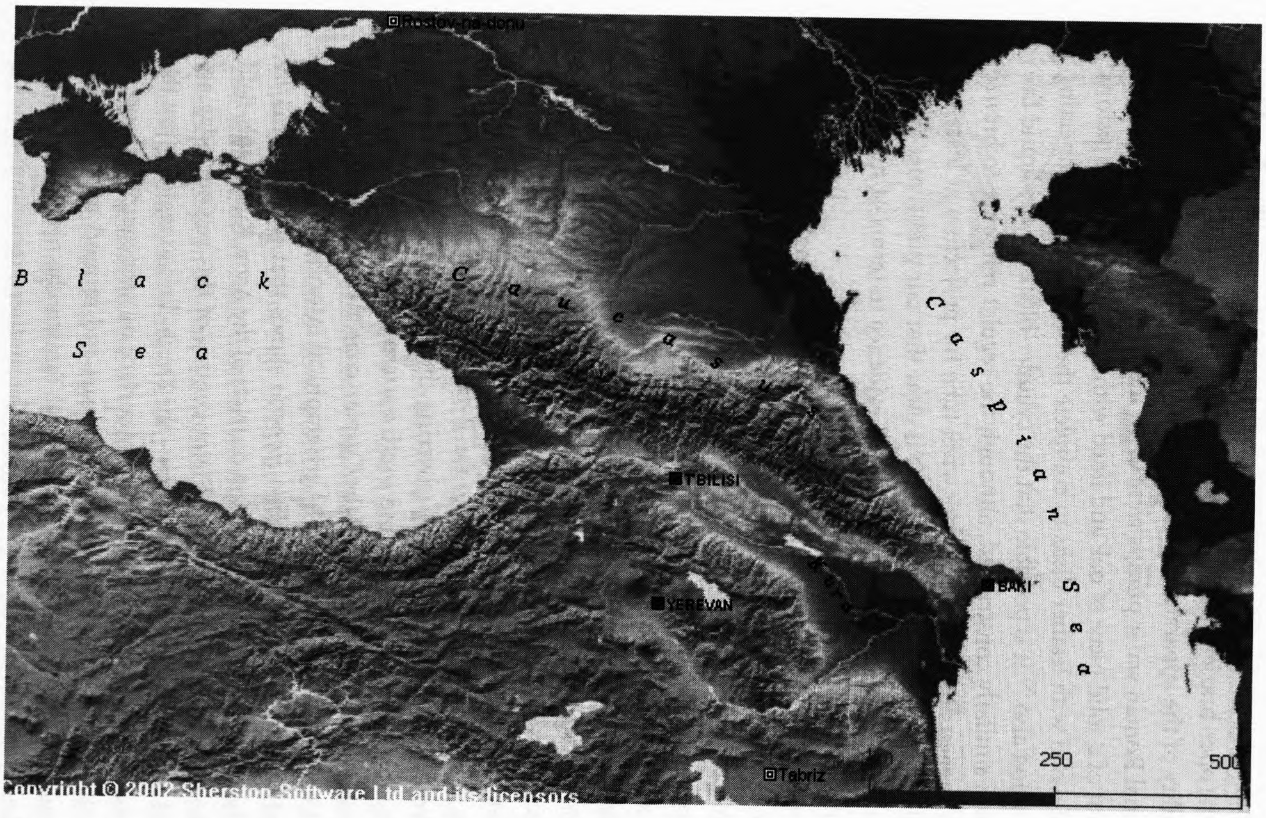
As can be seen from Fig. 15.1, our machine is differently proportioned and simpler in its basic mechanism than the water pumps excavated from western European Roman sites, but it would be relatively straightforward to reproduce these more exactly. Our machine was robust and very simple to operate, however, and ease of construction and robustness must have been important aspects of its design given that it was produced in considerable numbers for the imperial war fleet in the tenth century. If the contemporary accounts are to be accepted at face value, there must have been a need for a minimum of some 140 such devices for the expedition of 949, for example.[52]

We designed and operated this experimental prototype with a separate reservoir, connected to the pump by the piping described above. But in the

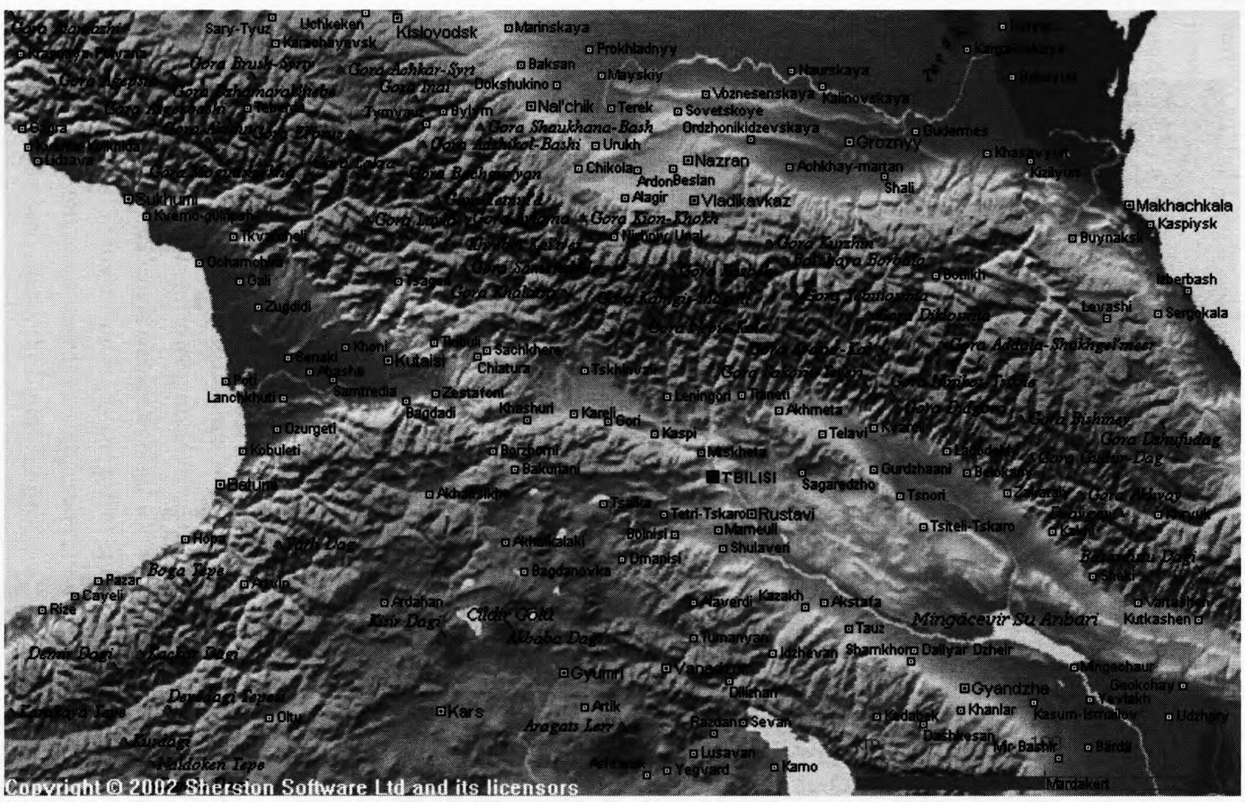
process of testing we were also able to demonstrate that by placing the cylinders inside the reservoir, the problem of leaking valves and wastage, and the potential dangers arising therefrom, could be overcome. The disadvantage of this design was in pre-heating the oil, since the operators would be standing next to the open brazier, subject to both heat and fumes; and in maintaining the stability of the apparatus during the fairly energetic pumping process. Traditional Roman water pumps were often made of wood – the cylinders bored out of a solid piece of oak and lined with lead or bronze, the pistons made of wood with leather disks to complete the seal, and the connecting rods of wood also.[53] It is possible that the cylinder-block for the liquid fire pump was similarly constructed, although the regular reference to bronze siphons suggests that the nozzle or swivel tube for projection at least was normally of this metal. In either case, it is clear that our pump met all the requirements of the ancient and medieval evidence in terms of materials, components and construction technique.

The nozzle: the Byzantine evidence reviewed above strongly suggests that the nozzle – the swivelling pipe through which the oil was actually aimed and projected – was constructed from bronze. Little is known about Roman fire-pump nozzles. The only extant nozzle is that from the Sotiel Coronada pump, and is part of the body of the pump rather than a separate element. We have no way of knowing exactly what proportions or form the Byzantine nozzle took, but our version cannot have varied except in small details from whatever was actually employed.[54]

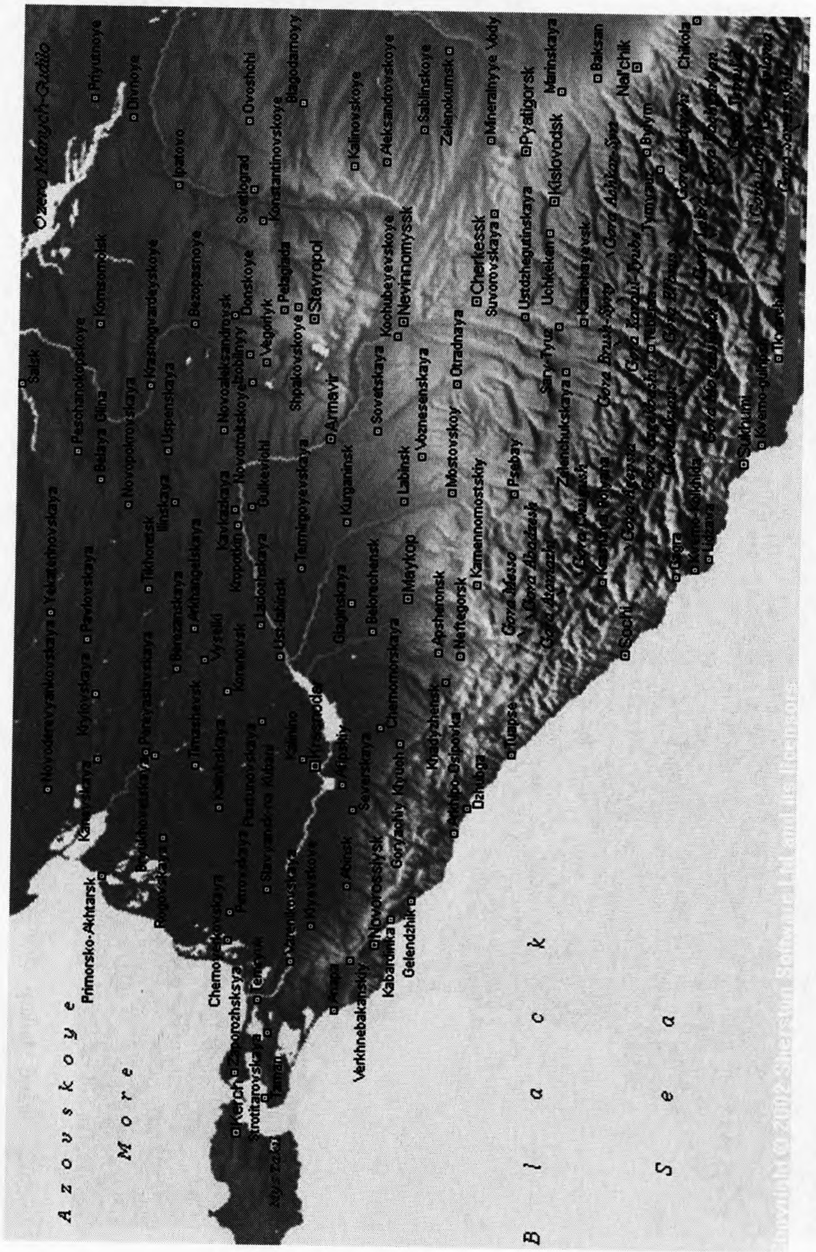
The oil: the liquid employed in the projector was an important consideration. The sources of oil known to the Byzantines lie entirely within the so-called North Caucasus oilfield, covering the regions from the eastern Crimea, north-western, eastern and south-eastern Caucasus, western Transcaucasia, western Turkmenia and the Caspian coastal zone of northern Iran (Figs. 15.5–7). More specifically, the geographical information provided by the tenth-century *De administrando imperio* shows that it was primarily from the north-western and Georgian districts of the Azov-Kuban sub-field that the empire drew its supplies. Major centres of this region today are focused around Maikop and Krasnodar – the Kerch-Taman region – but the area has long been known for the many surface oil seepages which occur along the northern foothills of the Caucasus and around to the Taman peninsula, where Tmutarakan, the medieval Tamatarcha mentioned in the *De administrando imperio*, is located; and the southern mountain zones in Georgia/Turkey around Ardahan and the Cildir Gölü in which Tziliapert was located – the nearest modern oil sources are in the Mirsaani and Patri-Shiraki districts of Georgia to the north.[55]



15.5 The Caucasus region



15.6 Taman and Maikop



15.7 Georgia

While the characteristics of the oil derived from these fields vary considerably, light crudes are common, with a predominance of paraffin-rich varieties low in non-hydrocarbons – in effect, easily inflammable.[56] Exposure to sunlight, water and evaporation when such oils seep to the surface inevitably involves loss of the lighter fractions and the reduction of the residue to a more tar-like substance – volatile products such as kerosene and gasoline may evaporate completely within a few hours and light crudes can lose up to 40 per cent within a 24-hour period; but where such seepages are from relatively shallow deposits it has been possible to dig wells or pits to extract the lighter, less-degraded crude with a greater percentage of the volatile components still present.[57] In the regions accessible to the Byzantines, however, the abundance of clays in the sediments through which the oil seeps contributes to strip out the heavier constituents, so that the surface seepages are lighter than in many other contexts.[58]

Thus the fact that it is – and was – such condensed and filtered light crudes which predominate in the Kerch-Taman region is especially important.[59] The Byzantines, or their agents, must have been able to collect substantial volumes of oil in a relatively non-viscous and non-tarry condition – presumably in large storage amphorae – and to store it in depots to which naval commanders or other authorized personnel had access, and these highly localized characteristics would suggest how that was possible. In 812, for example, the Bulgars captured 36 bronze siphons and the liquid fire projected through them at Mesembria, so it could clearly be stored for some time and still used.

Byzantine diplomatic relations with the Khazars during the eighth to tenth centuries played a central role in this, as is made clear both from the *De administrando imperio* and from the history of Byzantine–Khazar relations; while for the same reason relations with the Rus during the eleventh century and local rulers and client princes in the eleventh and twelfth centuries were of great importance to the empire. The loss of influence or control over Tmutarakan in the 1190s, the decline of imperial naval power at the end of the twelfth century, the intervention of the Cumans in the region at this time, the rivalry of Genoa, Venice and local rulers, and the arrival of the Mongols in the 1220s were probably the major factors in barring Byzantine access to sufficient quantities of oil to permit continued use of the weapon thereafter – as noted above, the liquid fire projector (as opposed to the age-old combustible projectile), disappears from the sources at precisely this time.[60]

For the purposes of the reconstruction and experiment we were able to obtain a 50-litre drum of a related light crude from a geologically associated

Azeri oilfield, thanks to BP Amoco.[61] The Byzantine sources refer frequently to the oil as 'prepared' (ἐσκευασμένον), or 'sticky' (κολλυτικόν) which we took to include the addition of resins to make the oil both more adhesive and to burn longer. And while heavier compounds raise the viscosity, the resin molecules in addition provide longer carbon chains than crude oil. Such longer carbon chains in turn burn at higher temperatures and thus make for a more effective weapon. The addition of organic resins to the oil, such as amber rosin (pine resin), naturally further complicated the issue, but in the experiment it became clear that heating the unrefined oil greatly reduced viscosity, permitting at the same time the admixture and blending of the resins, which were stirred in by hand as the oil was warmed on its brazier. We added about three kilograms of resin per 25 litres. We found that heating the mixed oil and resin to a temperature of some 60° C maintained a very fluid liquid, and also obviated the more solid elements blocking the pumping mechanism. We also found that where, after cooling, the oil and resin might have coagulated to constrict flow, lightly warming the piping freed the flow up very rapidly.

With our experimental device the separation of pump and reservoir meant that there was no negative impact from fumes or heat on the pump operators. Dangers from flashback between brazier and reservoir were countered by inserting a sliding cover across the top of the brazier, between reservoir and heat source; and by placing similarly a cover over the reservoir itself. In the Byzantine version, a flax-burning 'slow match' heat source (as we would argue the texts suggest: see below), in conjunction with an appropriately shaped reservoir to minimize the possibility of spillage under seagoing conditions, would have been relatively safe with such precautions. We surmised that, while the operators of the alternative design (pumping mechanism fixed inside reservoir) would be more exposed to toxic and noxious fumes as the lighter fractions of the oil evaporated off, this problem could likewise be overcome, along with the hazard of spilling oil as the ship moved, using the same method. While the version with pump mechanism, valves and oil fitted inside the reservoir would have been a very compact and versatile machine, the version we actually constructed and tested proved remarkably effective and easy to operate.

That heating was a part of the process is clear enough, and we would argue on the basis of this experiment that the original Byrne–Haldon suggestion, that the term πρόπυρον should be interpreted as 'pre-fire', i.e. the heating process, is correct. As we have already pointed out, fires could be contained in tiled metal grates or braziers on board wooden ships, and there is some indication that four-legged grates were a part of the device as a whole.[62] But a wood fire would be both too rapidly burned out (without constant stoking) and require a great deal more attention than the crew of a warship would be able to afford it. In this context, the textual evidence begins to make more sense. The inventory of materials required for warships in the expedition of 911/12, for example, notes: καὶ περὶ τοῦ ἑτοιμασθῆναι λινάριον λόγῳ τῶν προπύρων καὶ καλαφατήσεως χιλιάδας ι' ('and concerning the preparation of 10,000 (measures) of flax fibre for the *propyra* and the caulking'); while the *Tactica* of Leo states: τό τε ἐσκευασμένον πῦρ μετὰ βροντῆς καὶ καπνοῦ προπύρου διὰ τῶν σιφώνων πεμπόμενον ('the prepared fire projected from the siphons with thunder and smoke from the pre-fire'), the latter account neatly corroborated by the passage from the Yngvars saga.[63]

The quantities involved are clearly more than those required for the ignition flame on the siphon nozzle and thus, we would argue, imply a hearth of flax fibre which burns as a 'slow match', and is thus very safe in seagoing contexts, but which by the use of an ordinary bellows could rapidly be brought to a higher temperature, and thus heat up the oil once action became imminent. As noted above, in our experiment a metal tray was placed across the top of the brazier when it was felt the heat source needed to be reduced rapidly, and there is no reason to doubt that such a common-sense measure could or would have been adopted by the Byzantines. Flax fibre makes a great deal of smoke when it burns; the bellows would make a roaring, as does the projected oil once expelled and ignited. Our experiment showed that heating the oil greatly aided in reducing viscosity, by integrating the resins into the oil, and thus in facilitating projection without blocking the pump cylinders or valves. Indeed, even with relatively cool oil, viscosity was never such as to hinder in any way the smooth operation of the pump and projector, thus dealing with one of the objections which it has been suggested would make such a machine impractical.

Two things became immediately apparent in operating the machine. The first was that, in relatively calm conditions (which both Liutprand of Cremona and Anna Komnene make clear were necessary for the effective operation of the device) a fierce jet of flame could be directed for some seconds at a target up to 15 metres away (Figs. 15.8–9). Korres assumes, and cites supporting assumptions from others,[64] that a much greater distance would be required. But this is quite clearly not the case according to Anna Komnene, for example, one of whose accounts makes it clear that it could be used at very close range indeed.[65]

15.8 Boat burning in Malta

15.9 Boat burning in Malta

Ὁ δὲ λεγόμενος Ἐλεήμων κόμης, ἀναισχύντως μεγίστῳ πλοίῳ κατὰ πρύμναν προσβαλών, τοῖς πηδαλίοις τούτου περιπεσὼν καὶ μὴ εὐχερῶς ἔχων ἐκεῖθεν διαπλώσασθαι, κατεχέθη ἂν εἰ μὴ γοργῶς πρὸς τὴν σκευὴν ἀπεῖδε καὶ πῦρ κατ' αὐτῶν ἀφεῖς οὐκ ἄστοχα ἔβαλεν. Εἶτα τὴν ναῦν ἐπὶ θάτερα γοργῶς μεταφέρων καὶ ἑτέρας παραχρῆμα τρεῖς μεγίστας ἐπυρπόλει τῶν βαρβάρων ναῦς.

The count called Eleemon boldly made for a very large vessel by the stern, but fouled its steering-oars and found it hard to disengage, and he would have been caught, had he not quickly turned to the device (or: equipment/apparatus) and hurled fire at them with great accuracy. He then rapidly turned his ship in either direction and immediately set fire to three very big vessels of the barbarians.

In our practical demonstration, several jets lasting a few seconds were sufficient entirely to destroy a vessel at 10–15 metres, and indeed the heat was so intense that even without burning the target vessel it would have been sufficient to destroy the crew or force them to abandon ship. The heat was such that the operator needed substantial modern fire-protection and a shield between himself and the nozzle, and the Byzantine accounts likewise suggest that the device and nozzle were behind a protective bulwark and below an upper fighting platform. As the oil was expelled from the nozzle it burned with a loud roaring noise and a great deal of thick, black smoke – both features perfectly matching the accounts of some of the sources. It is worth pointing out that, in the description cited from Anna Komnene above, the range was clearly too close for a catapult-type device to have been employed effectively.

The second point is that the pump we built required at least three people to operate it – two on the pump, one directing the nozzle. The medieval references imply a single operator, as we have noted already; but in fact the simple copper connective piping we employed was several metres in length and could easily have been set out in such a way as to have the pump and reservoir some distance behind and possibly at a lower level than the nozzle and its operator. This would protect the pump crew, would obviate the danger of the flame from the nozzle being too close to the reservoir, and would also give the impression to an observer that the siphon operator worked alone. This remains hypothetical, of course, but it does show one possible configuration which fits the descriptions in the sources.

Finally, it became clear that spontaneous combustion upon contact with the atmosphere, as the oil was forced out of the nozzle, would not occur. Instead, therefore (and there is no source which suggests explicitly that any other method was employed), a small container was welded to the lower lip of the nozzle and filled with tow and hempen rope soaked in oil. When

ignited, this burned for some twenty minutes, proved to be a very effective torch as the main jet of oil was forced out of the nozzle and through this ignition flame, and was easily renewed under fighting conditions.

So far we have described the large, ship-mounted projector, with only a short comment on the so-called 'hand-siphon'. This remains a puzzle. The evidence noted already makes it clear that it was a hand-held projector. One source, although based on a much earlier third-century treatise, notes that it can be used to project liquid or prepared fire as well as noxious juices against horses,[66] which suggests strongly that it was in effect little more than a single-piston syringe – fuel or other liquids were drawn up from a reservoir and squirted out; alternatively, a reservoir attached to the body of the syringe provided fuel, which was drawn up a by a simple reciprocating valve mechanism. Illustrations of such a device have been noted from Islamic manuscripts of the thirteenth century and later, and it is not impossible that the form and structure of this hand-held device reproduced on a small scale the larger machine.[67]

In some accounts the term χειροσίφων could well describe small pots or *siphounia* hurled by hand, although the compound itself – 'hand-siphon' – would perhaps argue against this. In Leo's *Tactica*[68] it is noted that the 'small siphons' are discharged by hand and held by soldiers behind iron shields, that these are called hand-siphons, have been 'recently manufactured in our dominions', and 'also throw prepared fire into the faces of the enemy'. Hand-siphons are likewise listed among the equipment to be made ready for defending a city or fortress against enemy attack, deployed to burn the enemy's siege machines.[69] Given that simple syringes were certainly available before this time, it may be that the novelty consisted in the attachment to the syringe itself of a small tank or tube-shaped reservoir to give a slightly longer-lasting or more effective supply. It is difficult otherwise to explain the use of the phrase 'newly devised' in Leo's writings; and the illustration in the eleventh-century Vatican manuscript certainly supports this interpretation (if it can be relied upon, of course).[70]

If Eickhoff, Christide and others are correct that, on the basis of a handful of descriptions in Arab chronicles, Arab ships were equipped with such devices from the 830s onwards (perhaps, as Toynbee suggested, following a betrayal of the secret by the renegade officer Euphemios, *tourmarches* of the *thema* of Sicily),[71] then it is entirely possible that the large-scale fixed projector may have looked like these portable devices. In this case, we may imagine the main difference to have been the connection of the reservoir attached to the syringe by means of a pipe to the large reservoir of preheated

oil. From the point of view of the practical application of the concept, however, it is clear that it is possible to construct a relatively simple double-action pump of sufficient size and capacity and fuelled by preheated crude oil to project a fierce jet of flame a sufficient distance to incinerate an enemy crew and vessel with ease.

We have set out in the foregoing the basic evidence from the Greek and Latin sources for the operation of a liquid fire projector. It is clear that there are many points of uncertainty, and that more work remains to be done. We admit that our interpretation of the term *propyron* to refer to the preheating of the oil is only one possibility – the term might equally refer to the ignition-flame placed under the nozzle, and the flax referred to in the text in question may have been largely for caulking purposes – for the text in question is not specific. We do not know whether the Byzantines refined the oil, which may have produced a very different sort of device, and to which the term 'prepared' may also refer. There is no evidence that they did refine it, but nor is there any evidence whatsoever that they did, or could, not: there is absolute silence on this point.

The evidence for heating the oil is ambiguous and indirect in the Byzantine sources, and otherwise comes from western texts whose sources of information are unknown and may be inaccurate or contaminated. On balance, and given the evidence we had, we felt that heating the oil produced a more effective weapon, which our experiment appeared to bear out. It is also clear that a detailed account of the Islamic tradition in this respect, accompanied by a careful analysis of the texts and manuscripts involved, will greatly add to the discussion and perhaps clear up some of the uncertainties. But we believe that our well-planned practical experiment has shown what may and may not be achieved by developing some of the different and competing ideas that have evolved about the liquid fire ('Greek fire') projector. Using a simple force-pump, we demonstrated beyond any doubt that unrefined crude oil mixed with wood resin and heated over a brazier could be projected in a fierce flame (reaching over 1,000°) well over 10 metres to incinerate its target without danger to the crew of the machine or the ship on which it was mounted.[72]

Epilogue

'Liquid fire' was a relatively short-lived experiment in incendiary weaponry. Its use required adequate supplies of crude oil, and this condition could no

longer be secured after the later twelfth century, as the imperial fleet declined in numbers and efficacy and as the areas from which the oil had been collected became inaccessible to imperial agents. After Anna Komnene's account of its use and a small number of mentions for the twelfth century, the liquid fire projector itself appears no longer to have been in use by the time of the Fourth Crusade, although references in the written sources to pots and containers containing incendiaries and combustibles projected from catapults continue.[73] Whether the secret was indeed the privilege of a particular family of artificers and engineers at Constantinople or not, a story current in Byzantine times,[74] and whether or not the Arabs really possessed and employed a similar weapon, it has gone down in history as one of the most intriguing lost technologies of the pre-modern era. We can judge its importance only through the reports of those who employed it most effectively, the Byzantines. Whether we believe that it was wholly responsible for the naval victories ascribed to it or not, it provides a fascinating insight into both medieval military technology and medieval and modern myth-making.

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11. Th. K. Korres, *Ὑγρὸν πῦρ* (Thessaloniki, 1989).
12. See also *idem*, '"Greek fire": problems concerning the use of the "secret weapon" of the Byzantine navy', in *Αρχαία Ελληνική τεχνολογία: 10ο Διεθνές Συνέδριο της Εταιρείας Αρχαίας Ελληνικής Τεχνολογίας* (Athens, 1997), pp. 533–43.
13. Modern Tmutarakan, the region and city east of the Crimean Chersonese. Recent archaeological work in the area has recovered substantial numbers of so-called 'Tmutarakan pitchers', locally produced wares datable from the eighth century but most common in tenth- and eleventh-century contexts, a large proportion of which (some 80 %) contain chemical traces of naphtha on their inner surface. These have been associated with the proximity of surface sources of naphtha and both domestic usage (lamps etc.) and export or shipment to Constantinople for use in liquid fire projectors. See S. A. Pletneva, 'Goroda tamanskogo poluostrova v kontse VIII–XII vekakh', in T. I. Makarova and S. A. Pletneva, eds., *Krym, Severo-vostochnoe prichernomor'e i Zakavkaze v epokhu srednevokov'ie IV–XIII veka* (Moscow, 2003), pp. 171–83; K. V. Kostrin, 'Issledovanie nefti iz srednevekovykh amfor, naidennykh bliz stanitsy Proletarskoi', *Sovietskaia Arkheologiia* 1 (1965), pp. 291–3. We are grateful to Jonathan Shepard for bringing this material to my attention. For further discussion and literature, see now J. Shepard, 'Closer encounters with the Byzantine world: the Rus at the straits of Kerch', in T. S. Allsen and P. Golden, eds., *Studies in Pre-Modern Russian History: essays in memory of Thomas S. Noonan* (forthcoming). We are indebted to the author for permission to read this important article in advance of publication.
14. Zichia is the coastal region about and to the north of Batumi, on the eastern shore of the Black Sea. On this area see Moravcsik and Jenkins, *DAI, Commentary*, p. 208.
15. As Toynbee, *Constantine Porphyrogenitus*, p. 329, notes, this is the Doric form of the word πηγή, 'well/spring'.

16. Modern Tercan in eastern Turkey, south-west of Theodosioupolis (mod. Erzerum), and approximately halfway between Erzincan and Erzerum. By the time of the *DAI* its district was a *thema*: see N. Oikonomidès, *Les Listes de préséance byzantines des IXe–Xe siècles* (Paris, 1972), p. 358; Moravcsik and Jenkins, *DAI, Commentary*, p. 209.
17. Modern Üçyol, Turkey (Georgian Gjuljabert/Gölebert), near Çildir, east of Ardahan and north of Kars. N. Oikonomidès, 'L'Organisation de la frontière orientale de Byzance aux Xe-XIe siècles et le *Taktikon* de l'Escorial', in *Actes du XIVe Congrès International des Études Byzantines*, vol. 1 (Bucarest, 1974), pp. 285–302 (repr. in *idem, Documents et études sur les institutions de Byzance (VIIe–XVe siècles)* (London, 1976), no. XXIV), see pp. 287–8. For a short period in the 950s the district appears to have been a *thema* right on the imperial frontier. See Oikonomidès, *Listes de préséance*, p. 355 and n. 381, with Map 1, and n. 51 below. J. D. Howard-Johnston, 'The *De administrando imperio*: a re-examination of the text and a re-evaluation of its evidence about the Rus', in M. Kazanski, A. Nercessian and C. Zuckerman, eds., *Les Centres proto-urbains russes entre Scandinavie, Byzance et l'Orient* (Paris, 2000), pp. 301–36, at p. 305 and n. 12, is not convinced by this possibility, however (which lacks any explicit textual support), and suggests instead that the absence of Tziliapert from the Escorial *Taktikon* (c. 971–5) means that this reference in the *DAI* was added after the composition of the main body of the treatise.
18. E.g. *Leonis imperatoris tactica* (in *PG* 107: 672–1120) (the better edition: R. Vári, ed., *Leonis imperatoris tactica* vol. 1 (proem., const. I–XI); vol. 2 (const. XII–XIII, XIV.1–38) (Budapest, 1917–22) remains incomplete), XIX.6; XIX.51 (= A. Dain, *Naumachica* (Paris, 1943), I.6; I.59); *Nicephori Urani Tactica*, VI. 56 (ed. Dain, *ibid.*, p. 83); *Sylloge Tacticorum, quae olim 'inedita Leonis Tactica' dicebatur*, ed. A. Dain (Paris, 1938), p. 53.8; E. McGeer, *Sowing the Dragon's Teeth: Byzantine warfare in the tenth century* (Washington, D.C., 1995), pp. 3–59 (text), pp. 61–78 (notes): at p. 21=I 15 (ll. 150–5); several references to the *sipho(u)nia* of the imperial warships occur in the annotated inventory from the Cretan expedition of 949 preserved in the mid-tenth-century *Book of Ceremonies* II.45: *Constantini Porphyrogeniti imperatoris De cerimoniis aulae byzantinae libri duo*, ed. J. J. Reiske (Bonn, 1829), cap. 45. See J. F. Haldon, 'Chapters II.44 and II.45 of the *Book of Ceremonies*: theory and practice in tenth-century military administration', *TM* 13 (2000), pp. 201–352, cap. 45, ll. 141, 157 f., 202; and cf. *DAI*, XIII.73 ff.; XLVIII.30.
19. See Leo, *Tact.* XIX.51; *Naumachica*, ed. Dain, I.59; *Niceph. Urani Tactica*, VI.56; *Yngvars Saga Viðfötla*, ed. E. Olsen (Copenhagen, 1912), an account based on an oral tradition datable to the eleventh or twelfth century (and see J. Shepard, 'Yngvarr's expedition to the East and a Russian inscribed stone cross', *Saga-Book of the Viking Society for Northern Research* 21 (1984–5), pp. 222–92). For the need for calm waters and low winds, and the possibility of deploying the weapon at extremely close range: *Liudprandi Antapodosis*, V.15 (see n. 3 above);

Anna Comnena, Alexias, ed. D. R. Reinsch and A. Kambylis (Berlin and New York, 2001), XI.10.4; XI.11.4.

20. *Naumachica* I.8, VI.7; A. A. Vasiliev, *Byzance et les Arabes*, vol. 2: *Les Relations politiques de Byzance et des Arabes à l'époque de la dynastie macédonienne (les empereurs Basile I, Léon le Sage et Constantin VII Porphyrogénète) (867–959)*, vol. 2, ed. H. Grégoire and M. Canard (Brussels, 1950), p. 150 (an account of the Arab historian Ibn al-Athir, of the siege of Dvin in 927/8, in which a single artificer is responsible for the liquid fire projector).
21. See also *Theophanis Chronographia*, ed. C. de Boor, 2 vols. (Leipzig, 1883–5), p. 499 (Eng. trans., *The Chronicle of Theophanes Confessor*, ed. and trans. C. Mango and R. Scott (Oxford, 1997), p. 683); and a later ninth-century reference in MS Wolfenbüttel, Cod. guelf. 96 Gud. lat., f. 157r–v. See B. Bischoff, 'Anecdota Carolina', in W. Stach and H. Walther, eds., *Studien zur lateinischen Dichtung des Mittelalters: Ehrengabe für Karl Strecker* (Schriftenreihe zur Historischen Vierteljahrschrift: Zeitschrift für Geschichtswissenschaft und für lateinische Philologie des Mittelalters, vol. 1, Dresden, 1931), pp. 6–7: *fistula facta aerea* ('a tube made of bronze') is used to squirt burning oil on the enemy.
22. *Sylloge tacticorum*, LIII.8; *Alexiad*, XI.10.2; XI.10.4.
23. *Yngvars Saga*; and the ninth-century Latin text referred to above (p. 293, n. 21): *in prima fronte navis facta fornace illi insidunt vas eneum his plenum subposito igne* ('they [the Byzantines] make a furnace in the bows of their ship, on which they rested a vessel of bronze filled with these oils'). In the list of materials taken on board ship in the 949 expedition to Crete, the text includes τετράκουλα εἰς τὰ σιφώνια, which may be the four-legged grates on which the reservoir or tank full of oil was placed. Compare the galley hearth on the Yassi Ada ship, which consisted of earthenware tiles embedded in clay and mounted in a raised iron grate or grill: G. F. Bass, 'Underwater excavations at Yassi Ada: a Byzantine shipwreck', *Archäologischer Anzeiger* 77 (1962), pp. 537–64, at pp. 547–51. Such arrangements have been found in many similar wrecks of the late Roman and medieval periods. Arabic accounts of the liquid fire projector, although of later date, appear to corroborate the presence of this element: see V. Christides, 'New light on the naval warfare in the eastern Mediterranean, the Red Sea and the Indian Ocean (6th–14th cent. AD)', *Nubica* 3.1 (1994), pp. 4–25, see p. 7 and n. 11.
24. *De Cerimoniis*, cap. 44 and 45, ed. Haldon 'Chapters II.44 and II.45 of the *Book of Ceremonies*', cap. 44, l. 114; cap. 45, ll. 200–2; Leo, *Tact.*, XIX.51 (Dain, *Naumachica*, I.59).
25. M.-F. Auzépy, *La Vie d'Étienne le Jeune par Étienne le diacre* (Aldershot, 1997), cap. 69 (p. 169, ll. 28–30). See also Partington, *A History of Greek Fire*, pp. 15–16 for other references. On ancient and Roman pumps, see R. Stein, 'Roman wooden force-pumps: a case-study in innovation', *Journal of Roman Archaeology* 17 (2004), pp. 221–50; older literature: A. Neyses, 'Eine römische Doppelkolben-Druckpumpe aus dem Vicus Belginum', *Trierer Zeitschrift* 35 (1982), pp. 109–21;

T. Schiøler, 'Bronze Roman piston pumps', *History of Technology* 5 (1980), pp. 17–38; *idem*, 'Bombas hidraulicas españolas', *Arbor* 149 (1994), pp. 53–73. The technology of Roman water pumps was simple but effective, and the very limited medieval evidence suggests that such devices never fell out of use throughout the eastern Mediterranean world. On transmission of the technology of force-pumps, see the contribution of T. Schiøler, in F. Minonzio, ed., *Problemi di macchinismo in ambito romano: macchine idrauliche nella letteratura tecnica, nelle fonti storiographiche e nelle evidenze archeologiche di età imperiale* (Como, 2004), pp. 65–86. We are indebted to Richard Stein for this reference.

26. Ed. C. Wescher, *Poliorcétique des grecs: traités théoriques, récits historiques* (Paris, 1867), p. 174.4–5 and p. 185.3. See D. Oleson, *Greek and Roman Mechanical Water-lifting Devices* (Toronto, 1984), pp. 28 f.; J. G. Landels, *Engineering in the Ancient World* (Berkeley, 1981), p. 202.
27. See LSJ, s.v. σίφων and H. and R. Kahane, 'Abendland und Byzanz III, Literatur und Sprache, B: Sprache', in *Reallexikon der Byzantinistik*, A I, fasc. 4–6 (Amsterdam, 1970–6), cols. 345–640, at col. 408.
28. See Bischoff, 'Anecdota Carolina' (n. 21 above), pp. 6–7.
29. Korres, *Ὑγρὸν πῦρ*, pp. 136 ff., 142 ff. For the mechanism of a torsion *ballista*, see E. W. Marsden, *Greek and Roman Artillery: historical development* (Oxford, 1969), pp. 24–47.
30. For a useful summary of the arguments set out in greater length in the book, see Korres, 'Greek fire' p. 534f.
31. See D. Nishimura, 'Crossbows, arrow-guides and the solenarion', *Byzantion* 38 (1988), pp. 422–35.
32. See G. S. Mastoropoulos, 'Σίφων – σ(ι)φούνι: ἐπιβίωση ἑνὸς ἀρχαίου (;) ἀγγείου', *Ἀρχαιολογικὰ ἀνάλεκτα ἐξ Ἀθηνῶν* 21 (1988), pp. 158–62. *Siphon* need not necessarily have to mean 'pump': it might equally refer to the container and tube, on analogy with this sort of flask, while the term *strepton* would mean, as originally suggested, the swivel nozzle by which the fire could be directed (as Anna Comnena, *Alexiad*, XI.10.2, emphasizes). The original interpretation could thus be maintained without having to make a strong argument for *siphon* as 'pump'.
33. Korres, 'Greek Fire', p. 538 and n. 31 and Christides, 'New light on the naval warfare in the eastern Mediterranean', p. 5.
34. Auzépy, *La Vie d'Étienne le Jeune*, cap. 69 (p. 169.28–30): (τοὺς ἐν αὐτῷ τῷ τόπῳ ἱσταμένους ὑδροστάτας τῶν ἐμπρησμῶν, οὕσπερ σίφωνας καλοῦσιν), καὶ ἐξ ἑνὸς τούτων ξύλον μέγα λαβόμενος, ὅπερ ἀντίν λέγουσιν . . .' '(. . .) and taking the large wooden bar, called a loom, from one of them . . .'
35. Ed. Haldon, cap. 45, p. 141 (*De Cer.*, p. 672.3); pp. 157–8 (*De Cer.*, p. 673.10).
36. *Antapodosis*, V.15; S. H. Cross and O. P. Sherbowitz-Wetzer, *Russian Primary Chronicle* (Cambridge, Mass., 1953), p. 72.
37. Dain, *Naumachica*, I.6 (= VI.5) and discussed by Christides, 'New light on the naval warfare in the eastern Mediterranean', pp. 16–17.

38. See Haldon and Byrne, 'A possible solution', p. 95, n. 12. The only pictorial evidence apart from these Byzantine references for a hand-held 'siphon' occurs in an Istanbul manuscript (Topkapi Ms. 3469) of the 15th century, where the text, accompanied by an illustration, shows a syringe/piston-pump, or *zarraqa*, attached by pipes to a brass box containing distilled oil. See Ahmad Y. al-Hassan and D. R. Hill, *Islamic Technology: an illustrated history* (Cambridge, 1986), pp. 106–12, and 144–6. But the late date of the manuscript should encourage some caution in taking the illustration at face value.
39. Leo, *Tact.* XIX.57 (= *Naumachica* I.65; VI.60); *Sylloge tacticorum*, LXIII.8. For the *Parangelmata poliorketika*, see D. F. Sullivan, *Siegecraft: two tenth-century instructional manuals by "Heron of Byzantium"* (Washington, D.C., 2000), XLIX.20.
40. E.g. *Naumachica* I.61, 62, 64.
41. W. Schmidt, ed., *Heronis Alexandriae Automata et Pneumatica* (Leipzig, 1899), I.28.
42. A. Adler, ed., *Suidae Lexicon*, 5 vols. (Leipzig, 1935, repr. 2001), vol. 4, no. 1193 (στρεπτός) and 1194 (στρεπτούς) (pp. 442 f.).
43. See *Parangelmata poliorketika*, ed. Sullivan, cap. 45 (pp. 90–2).
44. See the discussion in P. E. Chevedden, 'Artillery in late Antiquity: prelude to the Middle Ages', in I. A. Corfis and M. Wolfe, eds., *The Medieval City under Siege* (Woodbridge, 1995), pp. 131–73; *idem*, 'The invention of the counterweight trebuchet: a study in cultural diffusion', *DOP* 54 (2000), pp. 71–116; and the literature in J. F. Haldon, *Warfare, State and Society in Byzantium 565–1204* (London, 1999), pp. 134–8. K. Huuri, 'Zur Geschichte des mittelalterlichen Geschützwesens aus orientalischen Quellen', *Studia Orientalia* (Soc. Orient. Fennicae) 9/3 (1941), pp. 51–63, 212–14, at p. 80, n. 2 thinks that a knowledge of torsion weapons may be indicated by a passage in the tenth-century *Parangelmata poliorketika* (see Sullivan, cap. 45, pp. 90–2), but since these passages are taken almost entirely from Heron of Alexandria's *Belopoeica* (ed. E. W. Marsden, *Greek and Roman Artillery: technical treatises* (Oxford, 1971), pp. 18–60, pp. 34 ff. and commentary pp. 55–60), the issue needs further clarification.
45. Theoph., pp. 353, 396–7.
46. For σκεύη, see Anna Comnena, *Alexiad*, XI.10.4 and below.
47. See the relevant sections in al-Hassan and Hill, *Islamic Technology*.
48. We would like to express our thanks to Windfall Films, whose support made this experiment possible and who thus contributed in no small way to the elucidation of several key issues. The programme was shown in the UK in July 2003.
49. In the practical test we certainly employed an unsuitably shaped reservoir, but it was immediately clear what shape would have been most appropriate on a ship subject to motion on the sea (conical – wider at the base than at the top; and circular in section, although cylindrical would not inhibit operations once the notion of a pressurized container is abandoned).

50. See also the paraphrase of Ctesibius, in Philo of Byzantium's *Belopoeica* (late third century BC), 77–8 (ed. Marsden, *Greek and Roman Artillery*, pp. 153–4).
51. See C. Fensterbusch, ed., *Vitruvii de architectura libri decem* (Darmstadt, 1964); for Hero, see note 39 above. No complete rocker has been found, although the iron parts of one composite rocker (of wood and iron) have been excavated: for the extant examples, from Italy, Britain, Gaul and Spain, see esp. Stein, 'Roman wooden force-pumps'. See also Schiøler, 'Bronze Roman piston pumps'; *idem*, 'Bombas hidraulicas españolas'; and with useful illustrations, F. Russo, 'Fuoco marino: tra leggenda e storia', *Rivista maritima* 137 (2004), pp. 55–68 (we are indebted to Nigel Wilson for obtaining a copy of this article).
52. See note 35 above.
53. See Stein, 'Roman wooden force-pumps', pp. 232–8, and figs.
54. We are particularly indebted to Richard Stein for much helpful comment and discussion regarding pumps and nozzles. See T. Schiøler, 'Die Technik und Technologie römischer Bronzepumpen: zu einem Fund aus Aventicum/VD', *Helvetia Archaeologica* 30 (1999), pp. 10 ff.; and esp. B. Päffgen and F. Willer, 'Bergung und Restaurierung eines Feuerlöschpumpen-Stahlrohres des 4. Jahrhunderts', *Archäologie im Rheinland 2002* (Stuttgart 2003), pp. 112–13; and Oleson, *Greek and Roman Mechanical Water-lifting Devices*. See also K. Maude, 'Roman force pumps', in N. J. Higham, ed., *Archaeology of the Roman Empire* (BAR International Series, 940. Oxford, 2001), p. 277 ff.
55. See E. N. Tiratsoo, *Oilfields of the World* (Beaconsfield, 1973), pp. 129–31; O. A. Radchenko, *Geochemical Regularities in the Distribution of the Oil-bearing Regions of the World* (Leningrad, 1965; Eng. trans. Jerusalem, 1968), pp. 113–17; D. B. Shelov, 'Neft' v Tanaise', in V. L. Ianin and others, eds., *Novoe v arkheologii: sbornik statei posviashchenyi 70-letiiu A. V. Artsikhovskogo* (Moscow, 1972), pp. 94–101; and the much older account in G. von Helmersen, 'Die Bohrversuche zur Entdeckung von Steinkohlen auf der Samarahalbinsel, und die Naphthaquellen und Schlammvulkane bei Kertsch und Taman', *Bulletin de l'Académie Impériale des Sciences de St-Petersbourg* 11 (1867), cols. 158–95. We are again grateful to Jonathan Shepard for bringing this material to our attention.
56. Radchenko, *Geochemical Regularities*, pp. 116–17.
57. Tiratsoo, *Oilfields*, pp. 28–30.
58. Radchenko, *Geochemical Regularities*, p. 117; Tiratsoo, *Oilfields*, p. 29.
59. The Georgian sources are less filtered, but are nevertheless, like the Azeri crudes from the Baku and Caspian regions, relatively light, with poor sulphur content and low tar levels. See Radchenko, *Geochemical Regularities*, p. 122.
60. See Shepard, 'Closer encounters with the Byzantine world', for detailed treatment of this aspect of Byzantine foreign policy; and T. S. Noonan, 'Byzantium and the Khazars: a special relationship?', in S. Franklin and J. Shepard, eds., *Byzantine Diplomacy: papers from the twenty-fourth Spring Symposium of Byzantine Studies,*

Cambridge, March 1990 (Aldershot, 1992), pp. 109–32; H. Ahrweiler, *Byzance et la mer: la marine de guerre, la politique at les institutions maritimes de Byzance aux VIIe–XVe siècles* (Paris, 1966), pp. 58 and 267.

61. Although this oil was in fact from a deep well, ref. GCA 6/6y (Dada Gorgud rig). Azeri is a light, low-sulphur crude oil, with greater proportions of kerosene at the expense of gasoil and naphtha. The oil from surface seeps or shallow beds collected by, or for, the Byzantines, will necessarily have been somewhat heavier owing to evaporation and biodegradation.
62. As in the Yassi Ada wreck, see note 23 above.
63. The inventory from 911/12: ed. Haldon, cap. 44, ll. 114–15 (*De* Cer., 658.12–14); Leo, *Tact.* XIX.51 (=Dain, *Naumachica*, I.59); *Yngvars Saga.*
64. Korres, 'Greek Fire', pp. 534, 536.
65. *Alexiad*, XI.10.4.
66. *Syll. Tact.* LXV (= Julius Africanus, *Cesti*, app. I.9): Προς φυγὴν δὲ ῥᾳδίως οἱ ἵπποι τρέπονται ἄν τινες τῶν Ψιλῶν καλουμένων πεζῶν τῶν ἀσπιδηφόρων ἱππέων ἑστῶτες ὄπισθεν χειροσίφωνά τε κατέχοντες χυλὸν ἐυφορβίου ἔχοντα τοῖς μυκτῆρσι τῶν ἵππων ἐμβάλωσιν, . . . 'Horses are turned easily to flight if some of the so-called light infantry stand behind the shield-bearing horsemen holding a hand-siphon containing euphorbium juice [Engl. milkweed/spurge] and hurl it into the nostrils of the horses . . .'
67. A reconstruction of possible versions of this device, based on the Islamic manuscript evidence (see n. 38 above), has been attempted: see *Αρχαία Ελληνική τεχνολογία: 10° Διεθνες Συνέδριο της Εταιρείας Αρχαίας Ελληνικής Τεχνολογίας* (Athens 1997), exhibition catalogue, nos. 9, 10, 11, 14, 15, 16.
68. XIX.57 (= Dain, *Naumachica*, I.65; VI.60). See further references in n. 39 above.
69. H. van den Berg, ed., *Anonymus de obsidione toleranda* (Leiden, 1947), p. 113. A team at Strathclyde University under the direction of Prof. J. Reese is currently working on building a full-scale working version of such a device. We are grateful to Prof. Reese and to Geraldine Paul for discussion.
70. Cod. Vat. graec. 1605, f. 185, C1. See nn. 37 and 38 above.
71. Incorrectly named as Euthymios by Toynbee, *Constantine Porphyrogenitus*, p. 330, with references to the Arabic sources and some of the modern literature; and the literature cited in n. 5 above. On Euphemios: *PmbZI*, no. 1701; *Prosopography of the Byzantine Empire 641–886*, ed. J. R. Martindale. CD-ROM (London 2000), Euphemios 1.
72. Dr Michael Lewis is preparing a detailed scholarly analysis of the whole question of 'liquid fire', its history and means of projection, to be published in the series *Birmingham Byzantine & Ottoman Monographs.* He proposes a somewhat different type of pump, and argues for a wider diffusion of the liquid fire projector across both the Islamic and Chinese worlds, but would agree with us in respect of the fundamental principles of the pump, the use of crude oil, and its effectiveness at close range. We would like to thank Dr Lewis for fruitful

discussion of the issues and for his generosity in showing us his manuscript in advance of publication.

73. See Haldon and Byrne, 'A possible solution', p. 98f. and n. 26; and above, p. 309, for the historical context through which the empire lost access to adequate supplies of the oil required.
74. See Partington, *A History*, pp. 20–1.